# Radio and Submillimetre Constraints on the Pulsar-Driven Supernova Model

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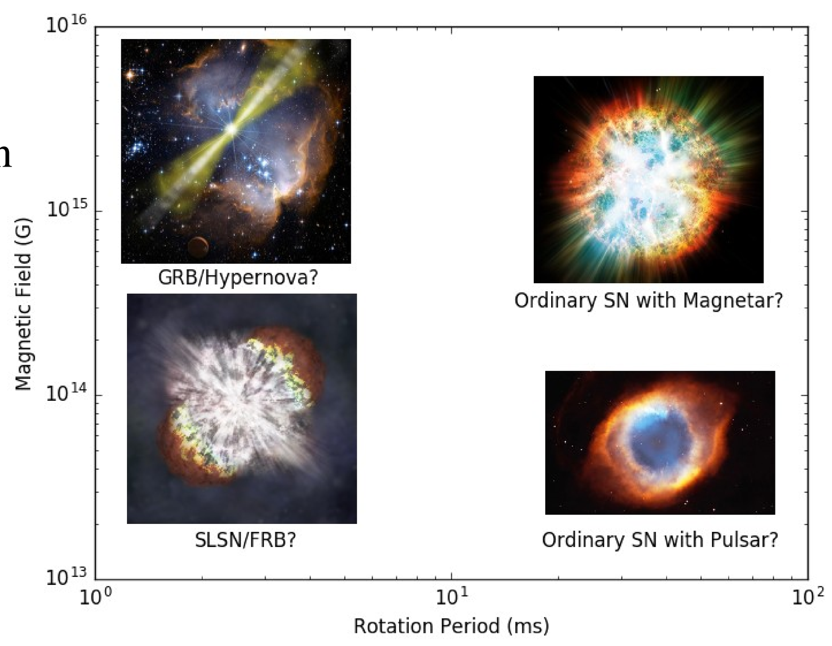
## Abstract

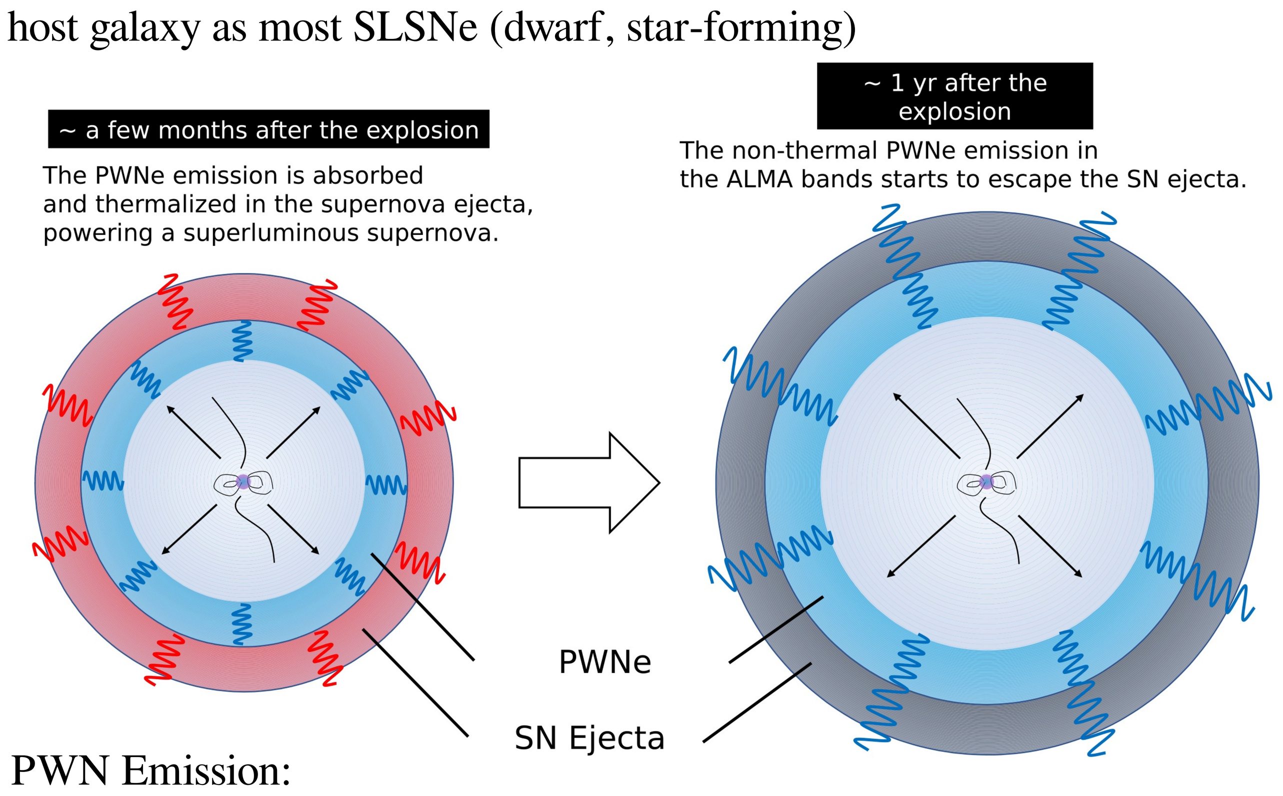
Today, large surveys detect thousands of supernovae a year, and our understanding of their causes, mechanisms, and aftermath is very thorough. However, there are several other transients, including Gamma-Ray Bursts (GRBs), Hypernovae (HNe), Super-Luminous Supernovae (SLSNe), and Fast Radio Bursts (FRBs), where the causes and mechanisms are less certain or even completely unknown. We explore the pulsar-powered supernova model as a method of unifying the diverse transients, and are concerned with a signal unique to this model, such as Pulsar Wind Nebula (PWN) emission. The smoking gun for this model should be late-time non-thermal emission, detectable after the ejecta becomes optically thin. We predicted the emission from several sources, and conducted follow-up observations in both radio (using VLA) and submillimetre (using ALMA and NOEMA). We found a weak signal from PTF10hgi, which was also detected at higher frequency by Eftekhari+ (2019), but no other detections, even though several observations had sensitivities well below our predicted lower limits. A likely explanation is that the assumed electron injection spectrum, which resembles that of the Crab, is wrong. Changing the spectrum to inject more electrons at higher energies creates a low energy spectral break which may explain the submillimetre non-detections. We calculate the time evolution of such a model and find it is consistent with both ALMA non-detections and the observed data for FRB 121102 and PTF10hgi.

## Background and Methods

- The pulsar-driven supernova model, where the spin-down energy of a rapidly-rotating pulsar powers the emission of the supernova, can explain the optical emission of transients like SLSNe and GRBs
- In order to test this model, non-thermal PWN emission needs to be observed, as any energy source can explain the optical emission - the energy gets thermalized in the optically thick ejecta in the early phase
- X-ray and gamma ray studies have found tentative candidates, but nothing too constraining




- Radio follow-up is another probe of PWN emission, but free-free absorption and synchrotron self-absorption attenuate the signal for the first ~ decade after the explosion
- Submillimetre signals are only attenuated for the first ~ year after the explosion
- FRBs are also thought to have similar pulsar progenitors to SLSNe, and FRB 121102 was localized to a similar host galaxy as most SLSNe (dwarf, star-forming)



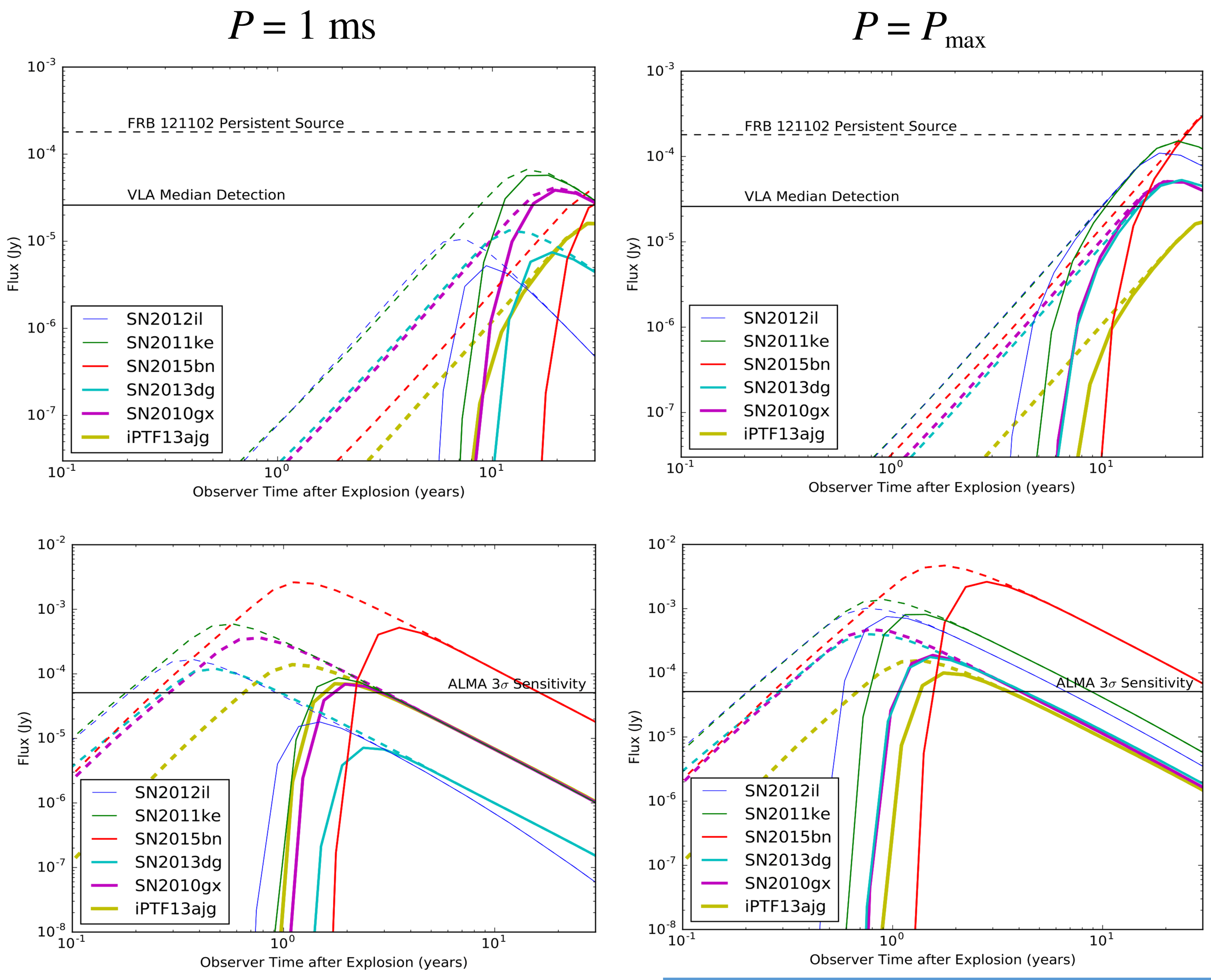

Radio/Submillimetre PWN Emission:

- We first fit the optical data of six recent SLSNe with the pulsar driven model to determine their initial rotation period $P$, initial dipole magnetic field $B$, and ejecta mass $M_{ej}$
- We then calculate broadband spectra for each SLSN and extract light curves at 1 GHz (VLA band) and 100 GHz (ALMA band)
- Our model includes acceleration of the ejecta due to the pulsar wind, an electron injection spectrum modeled from the Crab Nebula, pair production and cascades, scattering, free-free absorption, synchrotron self-absorption, and various types of high energy absorption

$P = 1$ ms $\qquad P = P_{max}$

1 GHz

100 GHz

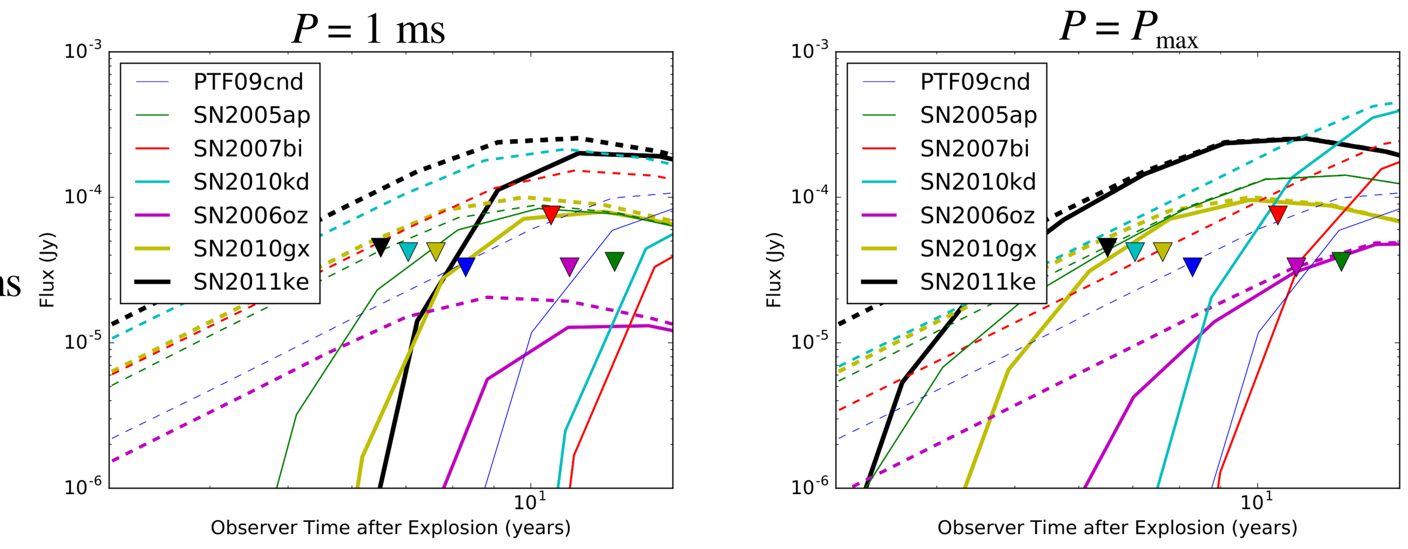



## VLA Observations

- We observed 10 SLSNe with VLA at 3 GHz
- We got 9 non-detections (including no FRBs), and one marginal detection from PTF10hgi
- The PTF10hgi detection is broadly consistent with our models, and some non-detections do constrain pulsar parameters, but SN2005ap should have been detected

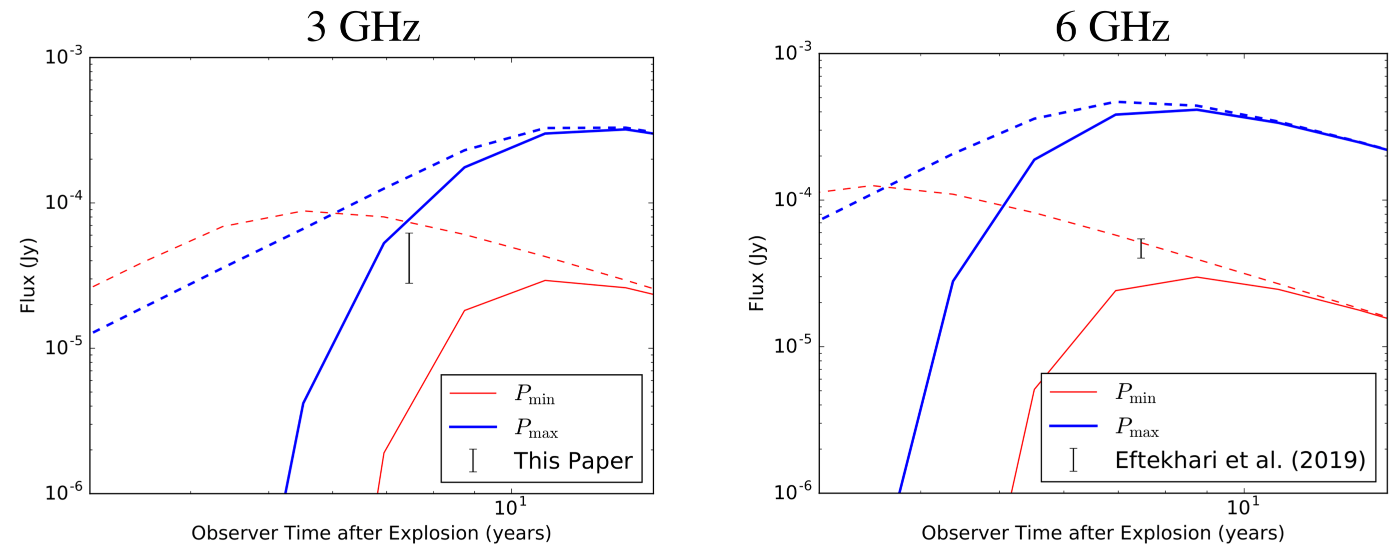
$P = 1$ ms $\qquad P = P_{max}$

Non-detections



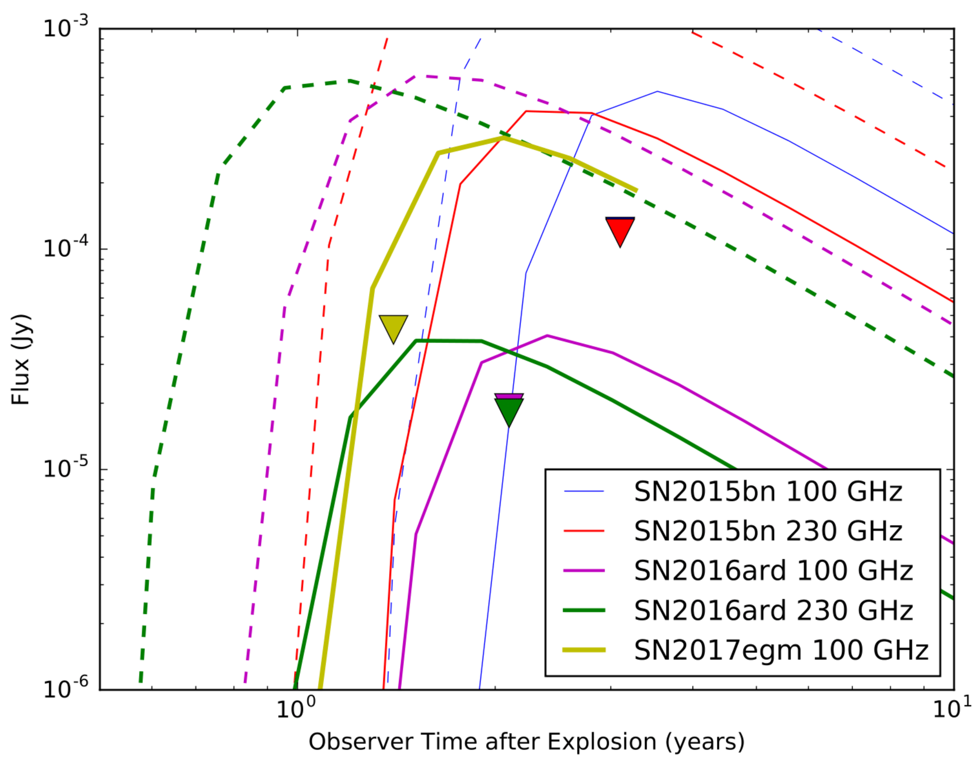

3 GHz $\qquad$ 6 GHz

PTF10hgi



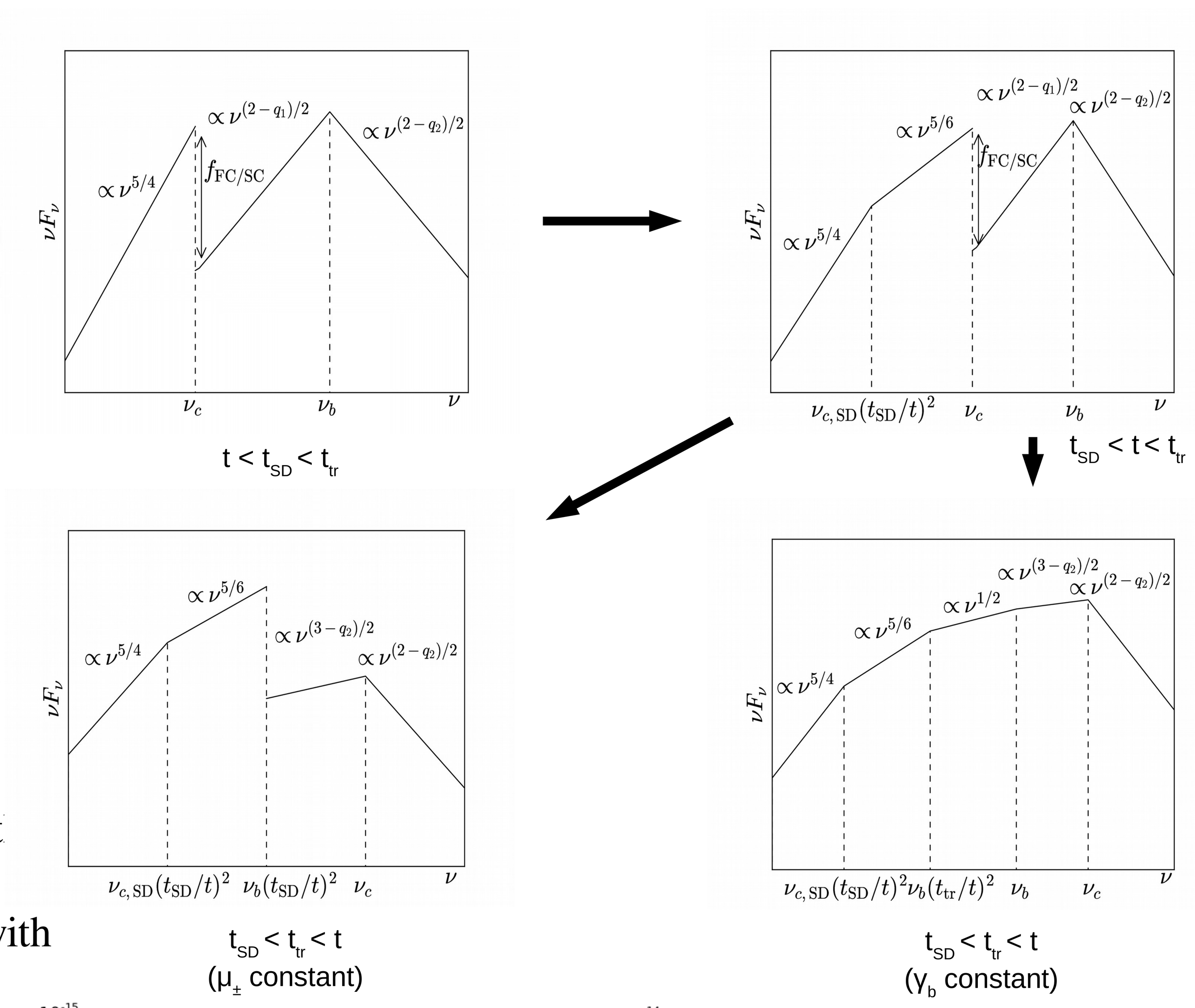

## ALMA/NOEMA Observations

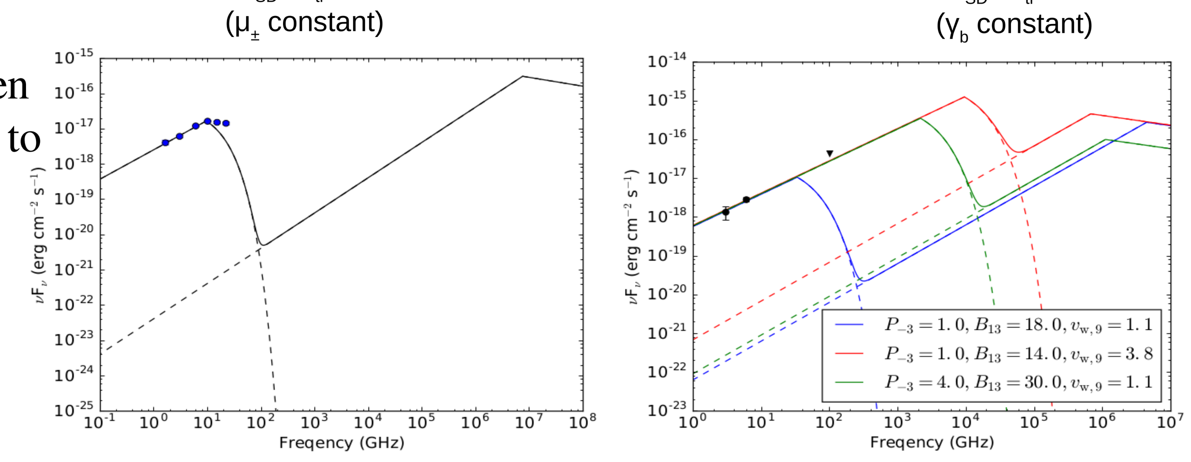
- We observed SN2015bn and SN2016ard with ALMA in bands 3 (100 GHz) and 6 (230 GHz), and observed SN2017egm with NOEMA in band 1 (100 GHz)
- We found a signal near SN2017egm, but it is coincident with a star-forming region in the galaxy, not the supernova remnant
- We observed no signal from SN2015bn and SN2016ard
- These non-detections below our predicted lower limits suggest something is wrong with our model




## Changing the Electron Injection Spectrum

- Changing the low energ injection to be less prominent results in a spectral break in radio
- The spectrum transition from fast-cooling to slo cooling at $t_{tr}$
- There are two extreme cases for late time evolution ($\mu_{\pm}$ or $\gamma_b$ constant)
- Low energy spectral indices are independent injection index
- Both FRB121102 and PTF10hgi can be fit wit this model with parameters consistent with other SLSNe
- Time evolution has been calculated, allowing us to predict the peak frequencies and fluxes




FRB 121102 $\qquad$ PTF10hgi